

LUNAR CAPILLARY ABSORPTION SPECTROMETER (LUCAS) FOR ISOTOPIC AND ABUNDANCE ANALYSIS OF LUNAR VOLATILES. I. R. King¹, F. J. Sheeran¹, J. Kriesel², A. Fahrland², J. C. Stern³, and the LuCAS team. ¹Honeybee Robotics (fjsheeran@honeybeerobotics.com), Altadena, CA 91001, ²Opto-Knowledge Systems, Inc., Torrance, CA 90502, ³NASA Goddard Space Flight Center, Greenbelt, MD 20771.

Introduction: Cold traps in Permanently Shadowed Regions (PSRs) at the base of polar lunar craters are known to contain volatiles, including water ice [1]. Locally sourced water is a critical resource for sustaining a human presence on the Moon as intended under NASA's Artemis program. However, the composition of the volatile mixture containing this water ice is not yet well-characterized, which makes the design of water harvesting systems challenging. To address this analysis need, we propose the Lunar Capillary Absorption Spectrometer (LuCAS): a novel end-to-end isotope and trace gas analyzer system for studying lunar volatiles.

LuCAS is comprised of a Sample Handling System (SHS) developed by Honeybee Robotics, and a CAS instrument developed by OKSI (Figure 1). The instrument can measure abundance and C, H, and O stable isotopic ratios of H₂O and CO₂ in regolith, in addition to measuring abundance of trace gases such as H₂S. Although LuCAS is compatible with a variety of sample collection tools, the team has baselined using Honeybee Robotics' Planetary Volatiles Extractor (PVEx) for its ability to extract and collect volatiles that are expected in the near-subsurface of the lunar poles [2].

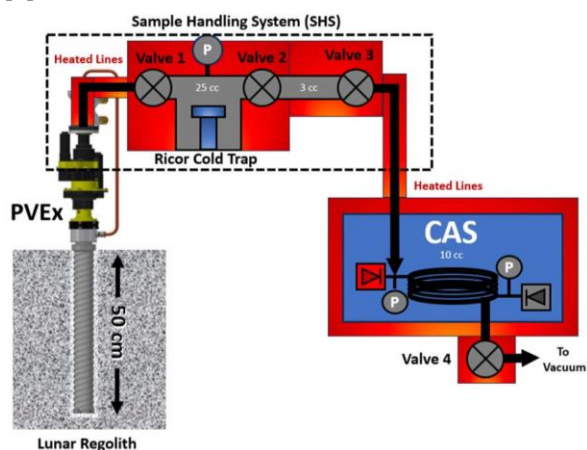


Figure 1: LuCAS diagram showing the path of lunar volatile analytes. Volatiles are extracted from the lunar surface by PVEx (left), collected in the SHS (middle), and metered in discrete aliquots into the CAS (right).

CAS Instrument: The CAS is an infrared laser spectrometer that provides unambiguous measurements

for both trace gas sensing and stable isotope analysis. Through use of a hollow and internally reflective fiber optic, CAS achieves near unity overlap between the laser beam and the gas sample in the fiber, leading to a highly sensitive system with an ultra-compact size. As a result, it performs measurements using a significantly smaller sample volume (~1 mL) when compared to state-of-the-art instruments like the Tunable Laser Spectrometer (TLS) on Sample Analysis at Mars (SAM) [3].

Lunar Volatiles Characterization: For lunar applications, the CAS can provide high precision abundance measurements of most of the volatile species that were observed during the LCROSS experiment [1], including H₂O, CO₂, CH₄, NH₃, and H₂S. Characterizing the composition of the native lunar ice mixture is of critical importance to the design of volatile collection systems for ISRU applications. While some of these species may be the target of extraction campaigns (notably, H₂O) others may be considered contaminants that are harmful to human health and robotic equipment (e.g. H₂S).

In addition to measuring abundance, the isotope information provided by CAS can shed light on the origin, formation history, and delivery of lunar volatiles. Specifically, different isotopic ratios of oxygen (e.g., ¹⁸O/¹⁶O) and hydrogen (D/H) will characterize the lifecycle of lunar water. For example, asteroid samples have similar ratios to those in earth's ocean while comets display a range of isotope ratios including higher D/H values [4]. Better constraining our scientific understanding of lunar volatiles can improve models that predict their presence and abundance across the lunar surface.

PVEx: The drilling system selected to extract and deliver volatiles to LuCAS is PVEx, a rotary percussive coring drill. Rather than extracting the core for analysis on the lunar surface like a traditional coring system, the PVEx coring auger has an embedded heater sleeve that heats the icy regolith in-situ. This volatilizes the ices, such that they can be collected and accumulated on a downstream cold trap. This is an energy efficient solution for extracting volatiles from the lunar surface and is robust to many different textures of ice and regolith mixture. This system has been tested to TRL 6

by the Honeybee Robotics team. A photo taken during this test campaign is shown in Figure 2.

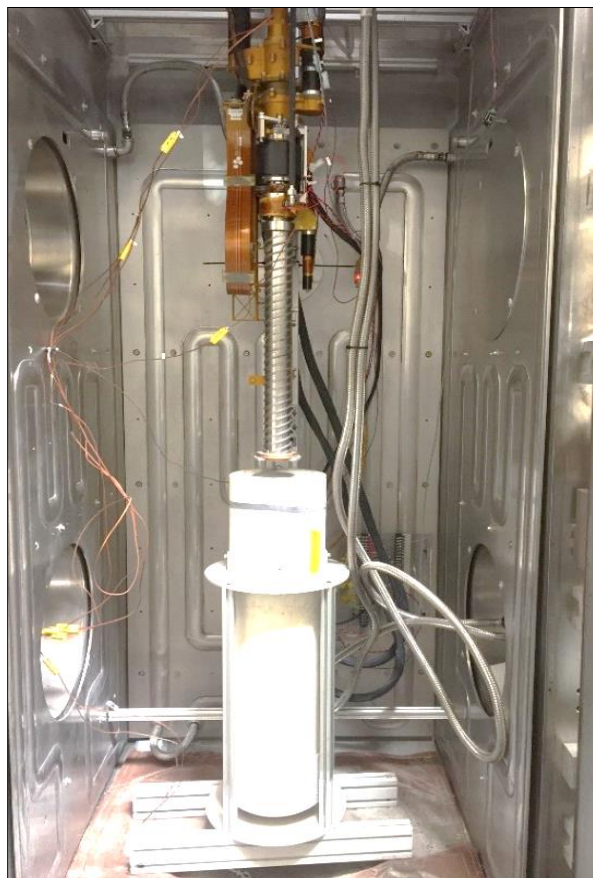


Figure 2: PVEx above an icy-regolith simulant bin in the thermal vacuum chamber at Honeybee Robotics.

LuCAS Development: Accurately characterizing the abundance and isotopic ratio of individual volatile species in a mixture of volatiles is a challenging process. Specifically, the challenge lies in minimizing memory and isotope fractionation effects on the measurement. This includes optimizing the material properties of surfaces exposed to the sample and controlling flow through a sample acquisition system like the combined PVEx and SHS.

LuCAS development work has been funded by SBIR Phase I and Phase II projects in addition to a recently awarded DALI. This has enabled the development of a TRL 4 breadboard of the SHS per the aforementioned principles and demonstrations of volatile delivery to the CAS. In these demonstrations, water standards (i.e., isotopically labeled water) are used to characterize the extent of memory and isotope fractionation effects. Results have demonstrated that the design enables successful delivery of samples with

different isotopic compositions as demonstrated by switching from deuterium-depleted to deuterium-enriched water standards. After just a few injections, LuCAS showed accurate and consistent isotope measurements, revealing minimal memory effects from the SHS. An example of these results are shown in Figure 2.

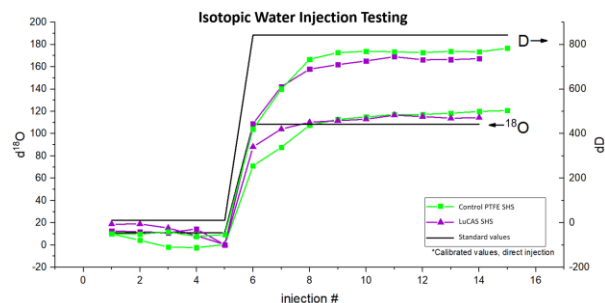


Figure 2: Water injection tests with known water standards comparing memory effects between the LuCAS SHS and an ideal PTFE volume.

Ongoing Work: Recently awarded DALI funding will develop LuCAS to TRL 6 and include an end-to-end test with PVEx in a thermal vacuum chamber with icy regolith to demonstrate applicability to future robotic missions.

References: [1] Colaprete A. et al. (2010) *Science*, 330, 463-468. [2] Zacny, K. et al. (2016) *ASCE*. [3] Kriesel, J. et al. (2023) *IEEE*. [4] Barnes, J. J. et al. (2016) *Nat. Commun.* 7:11684